V. COST AND COST-EFFECTIVENESS

The cost of NOx controls for reciprocating IC engines can vary widely depending on the individual site, size of engine, fuel type, type of engine, operational characteristics of the engine, and other parameters. For engines requiring the installation or replacement of major pieces of equipment, such as catalysts, engine heads, and turbochargers, the largest expense is the capital cost of controls. The replacement cost for catalysts can also be a major expense.

When an engine is controlled, greater care must be taken to assure that it is properly maintained, and thus maintenance costs may increase.

Fuel consumption may be increased by several percent for some of the controls. However, for some uncontrolled engines, modifications that lean the air/fuel ratio may decrease fuel consumption.

Depending on the existing equipment and requirements, other costs associated with achieving the determination’s requirements may include the purchase and installation of hour and fuel meters; purchase, installation, and operation of emissions monitors; source testing; permit fees; and labor and equipment costs associated with the inspection and monitoring program.

A. Costs for RACT/BARCT

The cost estimates in Table V-1 list the capital (including installation) cost for several of the most commonly used control techniques and technologies. Control techniques such as air/fuel ratio changes or ignition system improvements are not listed in Table V-1. These techniques are usually part of a collection of techniques such as a clean burn kit and therefore are included in those cost estimates already shown in Table V-1. However, the benefits and estimated costs of each separate technique is listed in Appendix B. The estimated costs shown in Table V-1 are considered general costs because of the wide variation in engine configuration and application used by the various industries in California as well as the variation in engine specifications within a series of engines produced by a manufacturer.

The cost shown in Table V-1 is a mixture of quotes and extrapolations of cost from information provided by industry sources, associations, local governments, and the U. S. EPA. It also includes an estimated cost for replacing engines in various horsepower ranges with an electric motor. Electrification may be a consideration as an alternative for internal combustion engines from 50 to 500 horsepower. Beyond that range, modification and installation costs may become so extensive that this approach may not be cost effective. The costs for electrification assume the units will be located relatively close to a power grid. If this is not the case, a cost of $5,000 to $10,000 may be incurred to have the local utility company install the appropriate power outlet for the motor to the local utility grid. In some utility districts, the cost for connecting to the power grid may be waived or refunded if the monthly energy usage matches or approach the cost to connect to the grid.

Table V-1
Cost Estimates for ICE Control Techniques and Technologies

Horsepower Range	Ign. Timing Retarding	Pre-Stratified Charge	NSCR[1] W/O AFRC	AFRC[2]	SCR[3]	Clean Burn Retrofit	Electrification[4]
50-150	$300	$10,000	$800-2,400	$4,200	$180,000	$14,000	$18,300
151-300	450	23,000	2,400-4,200	5,000	360,000	24,000	17,300
301-500	500	30,000	4,200-7,000	5,000	120,000	42,000	30,700
501-1,000	800	36,000	7,000-13,000	5,300	113,500	63,000	33,100
1001-1,500	900	42,000	13,000-19,500	5,300	132,000	40,000-256,000	92,400
1501-2,000	1,000	47,000	19,500-26,000	6,500	138,000	40,000-256,000	112,100
2,001-3,000	1,400				200,000	40,000-256,000	152,800

1. NSCR is an abbreviation for Nonselective Catalytic Reduction
2. AFRC is an abbreviation for air/fuel ratio controller
3. SCR is an abbreviation for Selective Catalytic Reduction. The costs are based on anhydrous ammonia injection, with parametric emissions monitoring system, and catalyst sized for 90 percent NOx conversion for lean burn engines.
4. The costs for electrification assume the units will be located relatively close to a power grid. If this is not the case, a cost of $5,000 to $10,000 may be incurred to have the local utility company install the appropriate power outlet for the motor to the local utility grid.

B. Cost-Effectiveness

Table V-2 lists the estimated cost-effectiveness for the control techniques and technology listed in Table V-1. It should be noted that these costs are estimates and may vary according to site-specific parameters, situations, and conditions. The costs for the different control technologies include the capital and installation costs. It also includes the expenses associated with additional maintenance and parts for the emission control, and the cost of additional or reduced fuel usage as a result of the control technology. In some applications, stationary engines are used to run compressors or generators. If the compressor or generator and the engine are an integral unit, then any additional costs incurred as a result of this integration should be included in the control equipment cost. Those additional costs are not reflected in the table.

For each control technique or technology, the cost effectiveness is based on an estimated percent of emission reduction of NOx from an uncontrolled engine. Some technologies, such as NSCR, can be used in stages to reduce emissions by having the exhaust gas flow through a series

Table V-2
Cost-Effectiveness Estimates for ICE Control Techniques and Technologies

Control	Horse Power Range	Capital Cost ($)	Installation Cost($)	O & M Cost($/year)	Annualized Cost ($/year)	Cost-Effectiveness ($/ton of NOx Reduced)
Ignition Timing Retard (@ 15% reduction)[3]						
	50 - 150	N/A	N/A	4,700	4,700	7,300
	151 - 300	N/A	N/A	3,400	3,400	2,100
	301 - 500	N/A	N/A	2,900	2,900	1,100
	501 - 1000	N/A	N/A	3,200	3,200	600
	1001 - 1700	N/A	N/A	3,300	3,300	100
Prestratified Charge (@ 80% reduction)[2,3]						
	50 - 150	10,000	N/A	1,000	2,700	800
	151 - 300	23,000	N/A	1,500	5,300	700
	301 - 500	30,000	N/A	2,000	6,900	500
	501 - 1000	36,000	N/A	2,500	8,400	300
	1001 - 1700	47,000	N/A	3,000	10,700	200
Nonselective Catalytic Reduction w/o AFRC (@ 90% reduction)[3]						
	50 - 150	11,000	2,500	7,200	9,400	2,500
	151 - 300	16,000	2,500	7,100	10,200	1,100
	301 - 500	18,000	2,500	7,900	11,300	700
	501 - 1000	28,000	2,500	9,500	14,500	500
	2500	44,000	2,500	11,400	19,000	300
Selective Catalytic Reduction for Lean Burn(@ 90% reduction)[1,3]						
	50 - 150	76,000	31,000	6,000	23,500	10,000
	151 - 300	112,000	45,000	12,000	37,600	8,000
	301 - 500	120,000	48,000	18,000	45,400	2,500
	501 - 1000	139,000	56,000	36,000	69,700	1,900
	1001 - 1500	132,000	56,000	46,000	78,500	1,500
Clean Burn Retrofit (@ 80% reduction)[2,3,4]						
	50 - 150	14,000	N/A	N/A	2,300	1,100
	150 - 300	24,000	N/A	N/A	3,900	1,000
	300 – 500	42,000	N/A	N/A	6,900	500
	500 - 1000	63,000	N/A	N/A	10,250	400
	1000 – 1500	40,000-256,000	N/A	N/A	6,500-41,700	100-900
	1500 - 2000	40,000-256,000	N/A	N/A		
Electrification[3]						
	50 - 150	18,300	7,400	unknown	4,200	1,200
	150 - 300	17,300	7,000	unknown	4,000	600
	300 - 500	30,700	12,300	unknown	7,000	500
	500 - 1000	33,100	13,300	unknown	7,600	300
	1000 - 1500	92,400	37,000	unknown	21,100	600
	1500 - 2000	112,100	44,900	unknown	25,600	600
	2000 - 3000	152,500	61,000	unknown	34,800	500

1 The cost for the SCR is based on anhydrous ammonia injection, with parametric emissions monitoring system, and catalyst sized for 90 percent NOx conversion.
2 The cost for fuel is not included in any calculation except for ignition timing retard.
3 The annualized cost do not include local costs such as permit fees, or cost for compliance assurance inspections or source testing.
4 Not Applicable (N/A). The costs for a clean burn engine or retrofit kit assume engine replacement or kit installation during the normal rebuild or replacement cycle of the existing engine.

of catalyst modules. In the case of ignition timing retard, fuel usage may increase by as much as 5 percent. The cost for the increased fuel use is included in the annualized cost shown in Table V-2 under that particular option. None of the other technologies are expected to increase fuel consumption drastically enough to contribute significantly to a cost increase. In fact, prestratified charge and clean burn technologies are expected to decrease fuel consumption because they result in a leaner burning engine. Likewise, operational and maintenance costs with the ignition timing retarded engine and the prestratified charged engine is not expected to increase significantly. The maintenance cost for the SCR system is associated with the use of ammonia and the maintenance of the SCR components, not necessarily with the engine directly.

Some technologies, such as clean burn, have nominal emissions limits specified by the manufacturer. The costs for a clean burn engine or retrofit kit assume engine replacement or kit installation during the normal rebuild or replacement cycle of the existing engine. By exchanging the older engine or installing a clean burn kit during an engine's regularly scheduled rebuild or replacement time allows a majority of the installation cost to be treated as a normal maintenance cost and not a cost directly incurred to achieve emission reduction. Because of the wide range of clean burn configurations for engines above 1,000 horsepower, those costs are listed as a range. Engines larger than 1,000 horsepower should be evaluated on a case-by-case basis.

The cost-effectiveness estimates were derived by first estimating annual costs for each control. The annualized cash flow method was applied to the pre-tax capital and installation costs using a nominal interest rate (including inflation) of 10 percent over a 10 year life. To this annualized cost were added the estimated additional annual fuel (where applicable) cost, plus operation and maintenance cost attributable to the control method. This sum yields the total annual cost which is listed as the "Annualized Cost" in Table V-2. It is assumed that the engines operate 2,000 hours per year.

Secondly, NOx reductions were estimated. The process used to determine reductions included selecting typical NOx emission rates from uncontrolled engines in each size category listed in Table V-2. Next, we estimated annual NOx emissions, and annual NOx emission reductions for each control method based on the percent NOx reductions listed for each control type in Table V-2. The cost-effectiveness is then calculated by dividing the "Annualized Cost" by the annual emission reductions. It should be pointed out that some of these control methods could result in reductions of other pollutants and/or an increase in fuel economy, which would be additional benefits.

It should be noted that the cost-effectiveness for prestratified charge (PSC) versus NSCR is very competitive in terms of pollutant reduced per dollar spent. In fact, if the cost of an air to fuel ratio controller is included with the cost of the NSCR, it becomes less cost-effective than the PSC. Also, the operation and maintenance cost for NSCR includes catalyst replacement after five years of operation. For lean burn engines, SCR is a very effective NOx reduction technology, but it is also relatively expensive for lean-burn engines rated at 300 horsepower or less. In that horsepower range, a clean burn retrofit is more cost effective.

As Table V-2 shows, cost-effectiveness for the selected technologies is equal to or less than $2,500 per ton of NOx reduced, with the exception of Ignition Timing Retard (ITR) for engines with horsepower rating below 150, and SCR on engines with horsepower ratings below 300. The higher cost-effectiveness for the ITR engines below 150 horsepower is due to the expected increase in fuel use. However, the cost-effectiveness for all of the controls listed are well below the $24,000 per ton bench mark used in this document and by some of the air quality districts. The installed and annualized costs for SCR are the highest in Table V-2. As mentioned previously, each engine site has to be considered on an individual basis along with the characteristics of each control type when considering emission reduction technologies.

Electrification cost-effectiveness is also estimated in Table V-2 for a range of engines up to 3000 horsepower in size. Below 500 horsepower, the installed costs associated with electrification are less than the installed cost for an equivalent internal combustion engine. Between 500 and 1000 horsepower, installed costs for electrification are comparable with that of an internal combustion engine. For engines larger than 1000 horsepower, electrification becomes very expensive with the primary advantage being that NOx emissions are reduced 100 percent although emissions from electrical power generating power plants will increase slightly.

C. Other Costs

The previous tables, for the most part, have covered the capital, operating, and maintenance costs for controls. Other expenses may also be encountered to comply with the proposed determination. In the case of hour meters and fuel meters, many engines already have such measuring devices, so there would be no additional cost. For engines using SCR, often the cost of a continuous NOx monitor is included in the cost of controls.

This proposed determination requires the use of an hour meter on exempt emergency standby engines operating fewer than 100 hours per year. In addition, many districts will likely require the use of fuel and hour meters for recordkeeping and compliance verification purposes. For completeness, the following information on these costs is provided as follows. Hour meters typically cost between $30 and $80 each, while a fuel meter with an accuracy of plus or minus three percent can range in cost from about $340 up to $4,500 depending on the manufacturer, fuel type, and fuel flow rate. A meter for gaseous fuel, such as natural gas, is more expensive than one for liquid fuels because gaseous fuel meters must compensate for pressure and temperature.

The proposed determination also requires the installation of an emissions monitoring system for engines rated 1,000 brake horsepower and greater and permitted to operate more than 2,000 hours per year. Costs of such a system vary depending on whether continuous emissions monitors are used or parametric monitoring is employed. The capital and installation cost of a continuous emissions monitor ranges from $25,000 to $100,000, and a parametric system ranges from $25,000 to $40,000. The annual operating and maintenance costs (per engine) are estimated to be $7,500 for a continuous emissions monitoring system, and $2,000 for a parametric emissions monitoring system. Costs are also associated with periodic source testing which is required to determine an engine's compliance with the emission limits. The cost of a source test is about $3,000 per engine using a reference method such as ARB Method 100. Costs are less if multiple engines are tested at the same time.

As part of the inspection and maintenance requirements, it is recommended that exhaust emissions be periodically checked with a hand-held portable analyzer. The cost of a hand-held portable analyzer is about $10,000 to $15,000. Many engine operators who perform their own maintenance and maintain several engines already use portable analyzers. Smaller operators generally contract out engine maintenance, and nearly all maintenance contractors already have analyzers. Thus, in most cases, requiring periodic checks with an analyzer is not expected to increase costs significantly.

D. Incremental Costs and Cost-Effectiveness

New requirements for the adoption of rules and regulations were passed by the State Legislature in 1995. These requirements, found in Health and Safety Code Section 40920.6, apply to districts when adopting BARCT rules or feasible measures. Specifically, when adopting such rules, districts must perform an incremental cost-effectiveness analysis among the various control options. Incremental cost-effectiveness data represent the added cost to achieve an incremental emission reduction between two control options. Districts are allowed to consider incremental cost-effectiveness in the rule adoption process.

When performing incremental cost-effectiveness analyses, in some cases an uncontrolled baseline may be appropriate. Table V-3 summarizes an incremental cost-effectiveness comparison for an uncontrolled baseline. For example, the costs for controlling an uncontrolled engine with the application of prestratified charge controls is estimated, along with the costs for replacing the engine with an electric motor. Emission reductions for application of these two different control methods to an uncontrolled engine are also estimated. The incremental cost-effectiveness is determined by dividing the difference in costs by the difference in emission reductions. The Table V-3 estimates were developed from the cost effectiveness analysis summarized in Tables V-2. For rich-burn engines, it was assumed that the prestratified charge technology would achieve an 80 percent NOx reduction and the NSCR control technology would achieve a NOx reduction performance of 90 percent control. Both of these technologies were compared against electrification as well as each other. The emissions reduction associated with electrification was assumed to be 100 percent. For lean-burn engines, incremental cost-effectiveness analyses compared electrification to clean burn, and SCR technologies. The results are included in Table V-3. The numbers in parentheses shown in Table V-3 indicates a saving per ton of NOx removed compared to the previous technology.

Table V-3
Incremental Cost-Effectiveness Estimates for ICE Control Techniques and Technologies

Engine Type	Control Comparison	Horsepower	Incremental NO_X Reduction (tons/year)	Incremental NO_X Cost-Effectiveness ($/ton of NO_X Removed)
Rich-Burn				
	From Pre-Stratified Charge to NSCR (90%)	50-150	0.4	(1,700)
		150-300	1.1	(400)
		300-500	1.8	(200)
		500-1000	3.5	(200)
		1000-1500	7.2	(100)
	From Pre-Stratified Charge to Electrification	50-150	3.5	(400)
		150-300	8.7	100
		300-500	14.4	0
		500-1000	28.4	0
		1000-1500	57.4	(400)
	From NSCR to Electrification	50-150	3.9	1,300
		150-300	9.8	500
		300-500	16.2	200
		500-1000	31.9	200
		1000-1500	64.6	(300)
Lean Burn				
	From Clean Burn to SCR (90%)	50-150	0.3	(8,900)
		150-300	0.5	(7,000)
		300-500	2.0	(2,000)
		500-1000	4.1	(1,500)
		1000-1500	5.9	(1,400 to 600)
	From Clean Burn to Electrification	50-150	2.1	(100)
		150-300	4.2	400
		300-500	16.4	0
		500-1000	32.8	100
		1000-1500	47.0	(500) to 300

Districts that adopt a BARCT level of control for IC engines may have already required a RACT level of control for these engines. Table V-4 summarizes data from Ventura County APCD and provides incremental cost-effectiveness estimates for the case where a RACT level of control has already been installed (i.e., baseline is RACT such as prestratified charge or NSCR designed to 90 percent control), and the control equipment is either modified or replaced to meet BARCT limits (i.e., NSCR with 96 percent control). It should be noted that Ventura APCD's analysis was performed for lean-burn engines reducing NOx emissions to 45 ppm or achieving reductions of 94 percent as opposed to our proposed BARCT limits of 65 ppm or 90 percent. The base NOx emission limits for this analysis are identical to our proposed RACT NOx limits.

Incremental cost-effectiveness values should be used to determine if the added cost for a more effective control option is reasonable when compared to the additional emission reductions that would be achieved by the more effective control option. Historically, when determining cost-effectiveness, districts have estimated the costs and emission reductions associated with controlling uncontrolled sources. This latter method is sometimes called "absolute" cost-effectiveness. Incremental cost-effectiveness should not be compared directly to a cost-effectiveness threshold that was developed for absolute cost-effectiveness analysis. Incremental cost-effectiveness calculations, by design, yield values that can be significantly greater than the values from absolute cost-effectiveness calculations. Direct comparisons may make the cost-effectiveness of an economic and effective alternative seems exceedingly expensive.

Table V-4
Incremental Cost and Cost-Effectiveness Summary for Application of BARCT to RACT Controlled Engines[1]

Engine/ Control	Size Range (HP)	Number of Engines	Reduction Needed (%)	Emissions Reduction (tons/yr)[2]	Capital Costs ($)	O&M Costs ($/yr)	Cost-Effectiveness ($/ton)[3]	Cost-Effectiveness ($/ton, adjusted to 1999 dollars)
Rich-burn								
From NSCR to improved NSCR								
	100-200	6	36	2.93	9,185	1,888	9,300	9,740
	225	1	22	0.37	9,185	1,888	8,200	8,590
	412	2	25	0.79	18,335	1,673	10,000	10,470
	625	1	19	0.79	18,260	2,399	6,000	6,280
	700-800	3	50	6.27	18,260	2,399	2,300	2,410
	1250	3	34	5.85	18,260	2,399	3,300	3,460
From PSC to NSCR								
	300	3	50	7.84	10,600	1,673	1,300	1,360
	330	3	53	0.62	10,600	1,673	17,000[4]	17,800
Lean-burn								
From SCR to improved SCR								
	660	2	62	14.81	105,000-346,500	15,000	3,800-7,900	3,980-8,270
From Clean Burn to added SCR								
	1108	8	29	39.38	105,000-346,000	15,000	6,300-13,000	6,600-13,610

1. Reference: Ventura County APCD Staff Report for Rule 74.9, December 1993
2. Based on actual emissions rate
3. Capital recovery factor of .125 used (approximately 9 percent interest for 15 years)
4. Operator proposed electrification for these engines